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Search for top squarks at Tevatron inspired by dark matter and electroweak baryogenesis

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ABSTRACT

The search for the top squark ($\tilde{t}_1$) within the kinematic reach of Tevatron Run II is of great contemporary interest. Such a $\tilde{t}_1$ can explain the baryon asymmetry of the universe provided 120 GeV $\leqslant m_{\tilde{t}_1} \leqslant m_t$. Moreover if $\Delta m \equiv m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ is small, where $\tilde{\chi}_1^0$ is the lightest supersymmetric particle (LSP), the dark matter relic density as obtained from the WMAP data may be explained via $\tilde{t}_1$-LSP coannihilation. In this scenario the decay $\tilde{t}_1 \to c\tilde{\chi}_1^0$ is likely to occur with 100% branching ratio but for small Δm the conventional di-jet + $\not{E}_T$ signal becomes unobservable. We propose a new search strategy based on the di-jet + $\not{E}_T$ signature accompanied by an isolated cluster of energy which arises from a decaying heavy particle with characteristic decay length. Our preliminary simulations with Pythia indicate that for 100 GeV $\leqslant m_{\tilde{t}_1} \leqslant$ 130 GeV this signal may be observable while somewhat lager $m_{\tilde{t}_1}$ may still provide hints of new physics.

1. Introduction

In the Minimal Supersymmetric Standard Model (MSSM) [1] there are two scalar superpartners $\tilde{t}_L$ and $\tilde{t}_R$, of the top quark which are the weak eigenstates. The mass eigenstates the lighter top squark ($\tilde{t}_1$) and the heavier top squark ($\tilde{t}_2$) are linear combinations of the weak eigenstates. Due to mixing effects in the top squark mass matrix in the weak basis driven by the top quark mass (m_t) there may be a significant mass difference between $\tilde{t}_1$ and $\tilde{t}_2$. In fact the former could very well be the next-to-lightest supersymmetric particle (NLSP), the lightest neutralino ($\tilde{\chi}_1^0$) being the lightest supersymmetric particle (LSP) by the standard assumption in R-parity conserving MSSM. This happens in a wide region of the MSSM parameter space. In this scenario, henceforth referred to as the $\tilde{t}_1$-NLSP scenario, the $\tilde{t}_1$ may be the only strongly interacting superpartner within the kinematic reach of Tevatron Run II experiments with a relatively large production cross-section.

Additional interest in the light top-squark scenario stems from the observation that the MSSM can explain the baryon asymmetry of the universe via electroweak baryogenesis (EWBG) provided 120 GeV $\leqslant m_{\tilde{t}_1} \leqslant m_t$ [2]. The search for $\tilde{t}_1$ is, therefore, a high priority program for the on going experiments at the Tevatron.

The search for $\tilde{t}_1$-NLSP at Tevatron Run I and LEP and, more recently, at Tevatron Run II produced negative results and lower bounds on $m_{\tilde{t}_1}$. Most of the analyses [3–5] are based on the assumption that $\tilde{t}_1$ decays via the Flavour Changing Neutral Current (FCNC) induced loop decay, $\tilde{t}_1 \to c\tilde{\chi}_1^0$ [6] with 100% branching ratio (BR). We also employ this assumption which is by and large valid if $\tan\beta$ is not too small, where $\tan\beta$ is the ratio of the vacuum expectation values for the two neutral Higgs bosons present in the MSSM[1] [7,8]. For small values of this parameter the four body decay of the $\tilde{t}_1$ may be a competing channel [7–9].

There are decay modes of the $\tilde{t}_1$-NLSP other than the above two channels. They are the tree-level two body decay, $\tilde{t}_1 \to t\tilde{\chi}_1^0$ and the three body decay, $\tilde{t}_1 \to bW\tilde{\chi}_1^0$. The last two modes are kinematically forbidden for small values of the mass difference $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ which is the main concern of this Letter.

The search for $\tilde{t}_1$-NLSP at the Tevatron are based on the jets plus missing E_T channel [4,5]. Some of the more recent works employed c-jet tagging by a lifetime based heavy flavour algorithm. These jets become softer if Δm is small. As a result the efficiency of the kinematical cuts for suppressing the background as well as

[1] It was shown in [7] for $\tan\beta = 2.5$ in MSSM the four body decay BR can be as large as 100%. This was followed by [8] where it was shown that for $\tan\beta \geqslant 7$ four body decay BR reduces to less than 10%. However one can find regions of the MSSM parameter space where the four body decay BR can be significantly large for $\tan\beta \approx 10$ (see the second paper of [8]).

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that of c-jet tagging decreases. This weakens the limit on $m_{\tilde{t}_1}$ from Tevatron. At Tevatron Run I the largest $m_{\tilde{t}_1}$ excluded was 122 GeV for $m_{\tilde{\chi}_1^0} = 55$ GeV. The most recent analysis by the DØ Collaboration at Run II [5] with c-jet tagging obtained the limit 150 GeV for $m_{\tilde{\chi}_1^0} = 65$ GeV for the most conservative cross-section after including the next to leading order (NLO) corrections [10].

On the other hand the LEP lower-bounds on $m_{\tilde{t}_1}$ are restricted mainly due to kinematics and are around 100 GeV [3]. However, much smaller values of Δm can be probed in the cleaner environment of an e^+e^- collider.

The prospect of $\tilde{t}_1$-NLSP search via this decay channel at Run II was investigated in [11]. It was observed that a large region of the $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ parameter space corresponding to small Δm is beyond the reach of Run II. For a given $m_{\tilde{t}_1}$ there is a minimum value of Δm that can yield an observable signal.

A modified strategy for $\tilde{t}_1$-NLSP searches in the limit of small Δm is important in its own right. The current interest in this search, however, is further strengthened by one of the cornerstones of the interface between particle physics and cosmology. A very attractive feature of the R-parity conserving MSSM is that the LSP ($\tilde{\chi}_1^0$), is a very good candidate for the dark matter (DM) in the universe required, e.g., by the Wilkinson Microwave Anisotropy Probe (WMAP) data [12]. The DM relic density depends on the annihilation cross-section (thermally averaged) of a LSP pair. The coannihilation of the LSP with any other supersymmetric particle (sparticle) is another important mechanism for relic density production. This mechanism is, however, efficient only when the two coannihilating particles have approximately the same mass. Thus in the small Δm scenario $\tilde{t}_1$-LSP coannihilation may indeed be an important mechanism for producing appropriate relic density [13].

The region of the parameter space of MSSM consistent with the DM relic density is severely constrained by the WMAP data. Nevertheless even in more restricted versions of the MSSM like the minimal supergravity model (mSUGRA) [14] one finds a narrow region of the parameter space where $\tilde{t}_1$-LSP coannihilation is an important relic density producing mechanism [15].

The search for $\tilde{t}_1$-NLSP with a small Δm is, therefore, important irrespective of the question of EWBG. However, it is certainly worthwhile to check whether $\tilde{t}_1$ with mass in the quoted range preferred by EWBG can also produce an acceptable DM relic density. This was investigated in [16]. It was found that in a significant region of the allowed parameter space Δm is indeed small (see Fig. 7 of the first reference of [16]). Our choices of δm in this Letter are guided by this paper.

The results of [16] were illustrated by specific choices of other MSSM parameters. In particular EWBG in the MSSM requires certain CP violating (CPV) phases. In a certain phase convention the relative phase (ϕ_μ) between the higgsino mass parameter μ and the SU(2) gaugino mass M_2 is the most important one. EWBG usually requires $0.05 \leqslant \phi_\mu \leqslant 1$. However, various uncertainties in the calculation does not rule out a much smaller magnitude of this phase. Thus calculations by neglecting this phase seems to be a reasonable approximation [16].

It should, however, be emphasized that the signal proposed by us is fairly model independent and does not depend on the CPV phase or many of the other MSSM parameters at all as long as the $\mathrm{BR}(\tilde{t}_1 \to c\tilde{\chi}_1^0)$ is close to 100%. Under this assumption the size of the signal depends on $m_{\tilde{t}_1}$ through the production cross-section of the $\tilde{t}_1$ pair via the standard QCD processes and on $m_{\tilde{\chi}_1^0}$ through the efficiency of the kinematical cuts.

The starting point of our work is the observation that when mass difference Δm is small, in most of the signal events, one of the c-quarks from $\tilde{t}_1$ pair decay is not energetic enough to produce a jet which may pass jet selection criteria of the experiments at Tevatron. It may be seen as an isolated energy deposit in the calorimeter coming from the decay of a heavy particle. We call it *isolated cluster* (*IC*). Thus the proposed signal consists of a c-jet of modest E_T accompanied by missing energy and an *isolated cluster*. In order to reduce the background we require another hard jet in the signal which in most cases comes from QCD radiation. Our simulations show that a set of selection criteria based on the above features of the signal can isolate it from the SM background.

In this Letter we do not consider the prospect of fully identifying the flavour of the heavy, isolated, decaying object because of the rather small statistics. This leads to inevitable backgrounds from, e.g., $b\bar{b}$ events and $W/Z+$jets events. However, we shall analyze at the generator level some important characteristics of this object which has the potential of reducing the SM backgrounds to a manageable level. At the same time we emphasize that this work is only suggestive of a new approach to $\tilde{t}_1$ search at the Tevatron and needs detailed detector simulation for a more definitive statement and that is beyond the scope of this work.

We have used Pythia (v 6.206) [17] for generation of both signal and background events which includes generation of the parton level events followed by the decay of the partons hadronization and decay of their daughters. Generation of both signal and background events take into account initial state radiation (ISR) and final state radiation (FSR). The cross-sections $\sigma_{b\bar{b}}$ and $\sigma_{c\bar{c}}$ are very large and most of these events generated with low $\sqrt{\hat{s}}$ are not relevant for our analysis. To sample the $b\bar{b}$ and $c\bar{c}$ events better for our purpose and save computer time we have used a cut $\hat{p}_T \geqslant 3$ GeV for generation of $b\bar{b}$ and $c\bar{c}$ events, where $\hat{p}_T$ is defined in the CM frame of the colliding partons. We have used the toy calorimeter simulation followed by jet formation in Pythia (PYCELL).

1. The calorimeter coverage is $|\eta| \leqslant 3$.
2. A cone algorithm with $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.5$ has been used for jet finding with $E_{T,\min}^{\text{jet}} \geqslant 10$ GeV and $|\eta_{\text{jet}}| \leqslant 3$ and jets have been ordered in E_T.
3. We consider leptons ($\ell = e, \mu$) with $E_T^\ell \geqslant 5$ GeV, $|\eta^\ell| \leqslant 3$. The lepton should be isolated from jets ($\Delta R(\text{jet}, \ell) \geqslant 0.5$).
4. For charged particles (e, μ and charged hadrons), we have used their generator level momentum as *track momentum* when required.
5. For jets containing a B or a D hadron we have used their decay length information for determining the presence of a long lived particle.

A quark or a gluon from (mainly) FSR is seen as a jet and in most cases this jet appears to have the highest E_T. This prompts us to consider a rather unusual signature for the signal events as mentioned below.

The backgrounds events, particularly $b\bar{b}$ and $c\bar{c}$ have very large cross-sections and hence we need to generate a large number of events and retain only a small fraction of them which pass preselection for detailed analysis. We have used the following preselection criteria:

1. Event should have only two jets: $N_{\text{jet}} = 2$ (see Fig. 1).
2. Events with isolated leptons are rejected.
3. One of the jets should contain a long lived particle (B or D hadron) and henceforth called *matched-jet* (*MJ*).
4. Event should have an *isolated cluster* resulting from the decay of a B or D hadron such that $\Delta R(\text{jet}, IC) \geqslant 0.5$. The direction of the *isolated cluster* is defined to be the direction of the decaying B or D hadron. In the final selection this cluster has to be identified as the signature of a long lived particle, the criteria for which are discussed in detail later.
5. We assume that a *b-jet* with 30 GeV $< E_T^{\text{jet}} <$ 50 GeV is tagged with a probability $\epsilon_b = 0.4$ and for $E_T^{\text{jet}} > 50$ GeV, $\epsilon_b = 0.5$